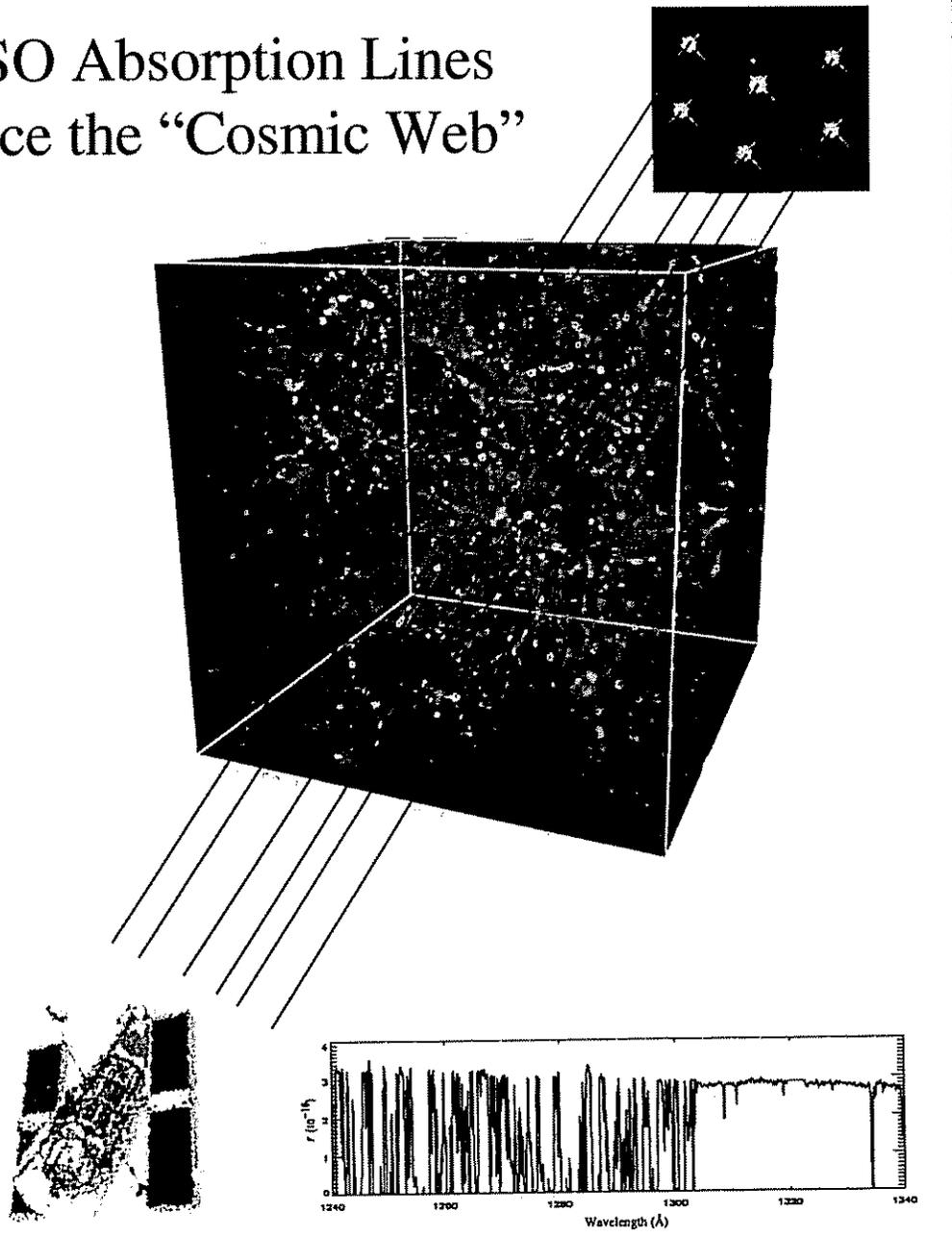


Large-scale Structure and the IGM

QSO Absorption Lines
trace the “Cosmic Web”



- Visualization concept from Schiminovich & Martin
- Numerical simulation from Cen & Ostriker (1998)
- Songaila et al. (1995) Keck spectrum adapted by Lindler & Heap

Ly α Forest [Q 0302-003]

$Z_{em} = 3.29$

Keck 10^m Tel.

[Songaila, Hu, Cowie
Nature 1995]

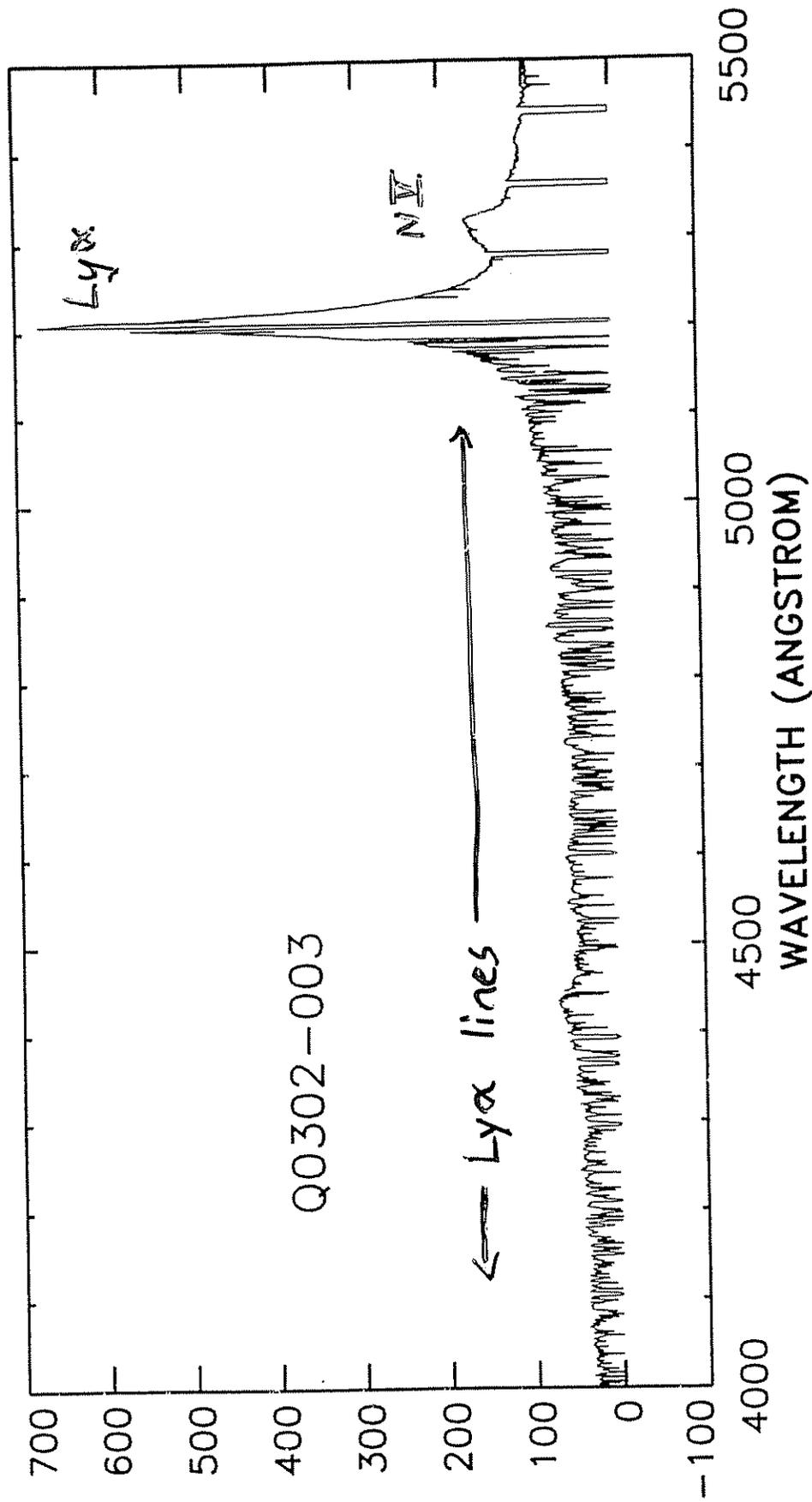
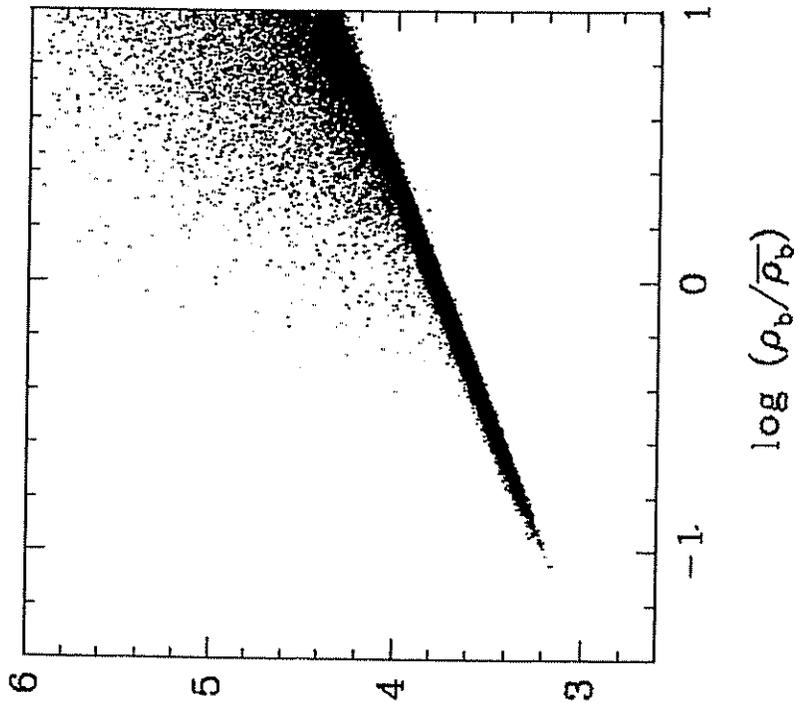
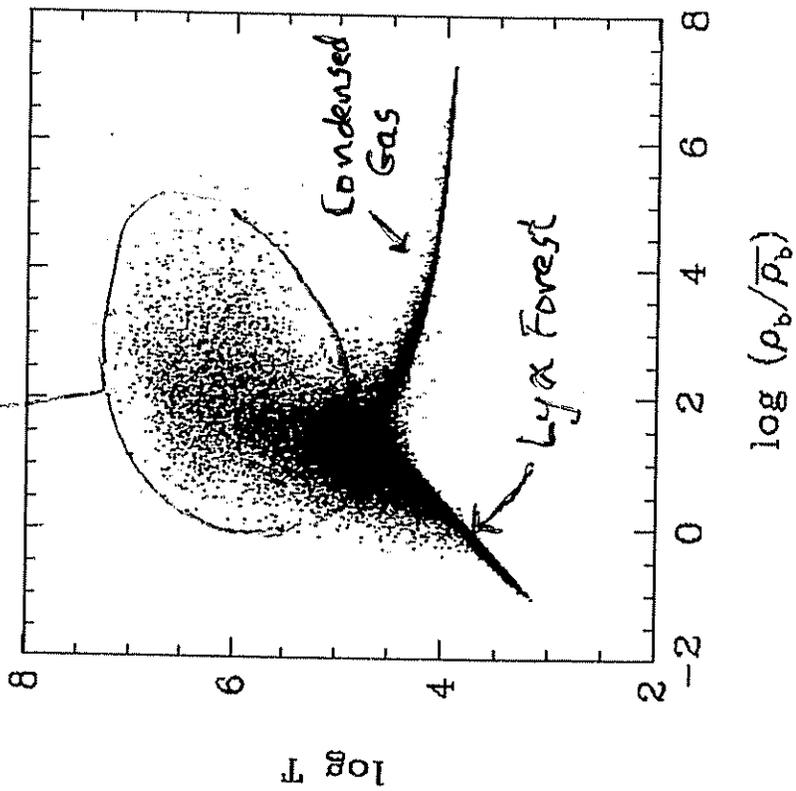


Fig. 1

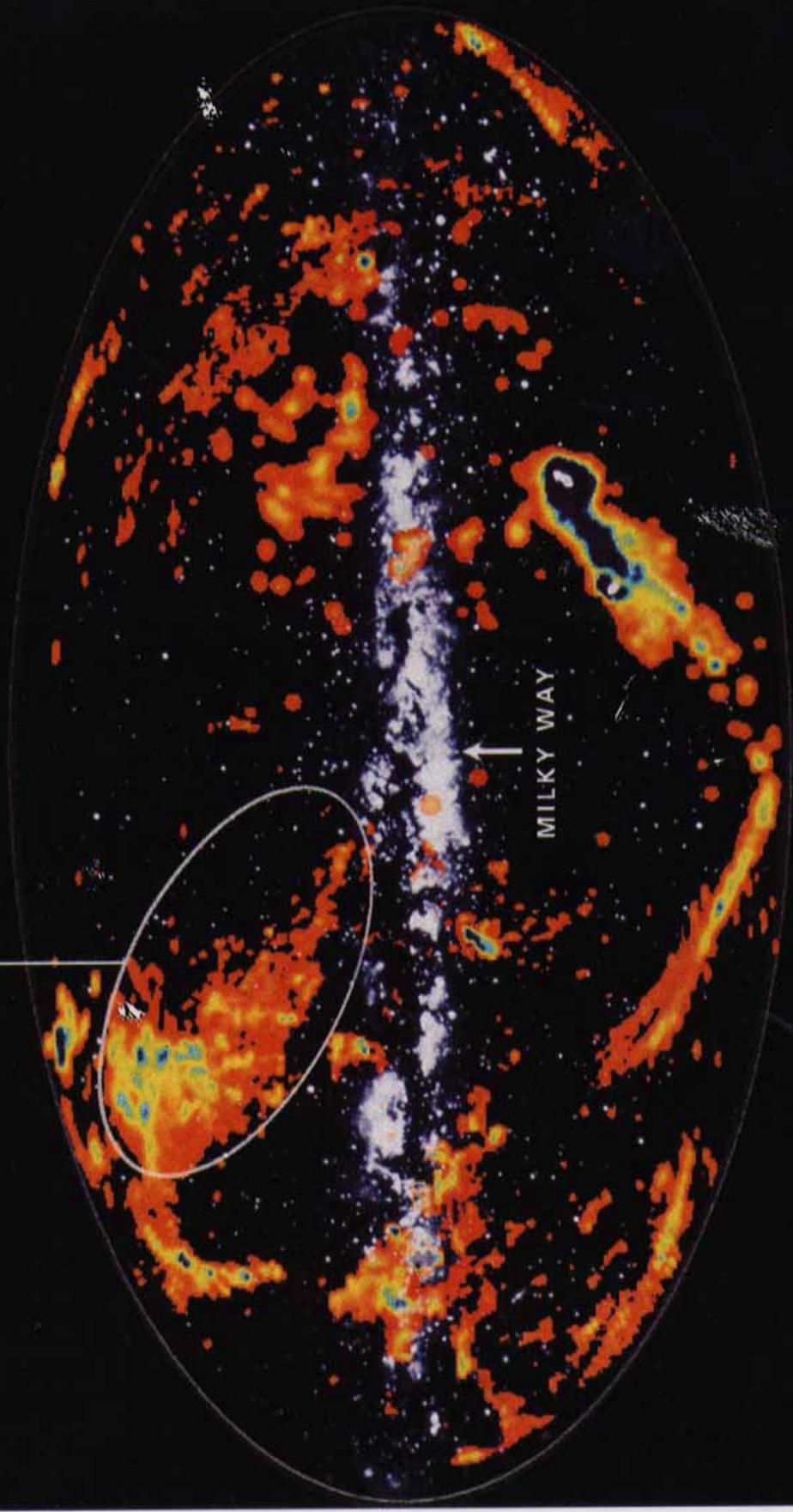
hot, shocked IGM



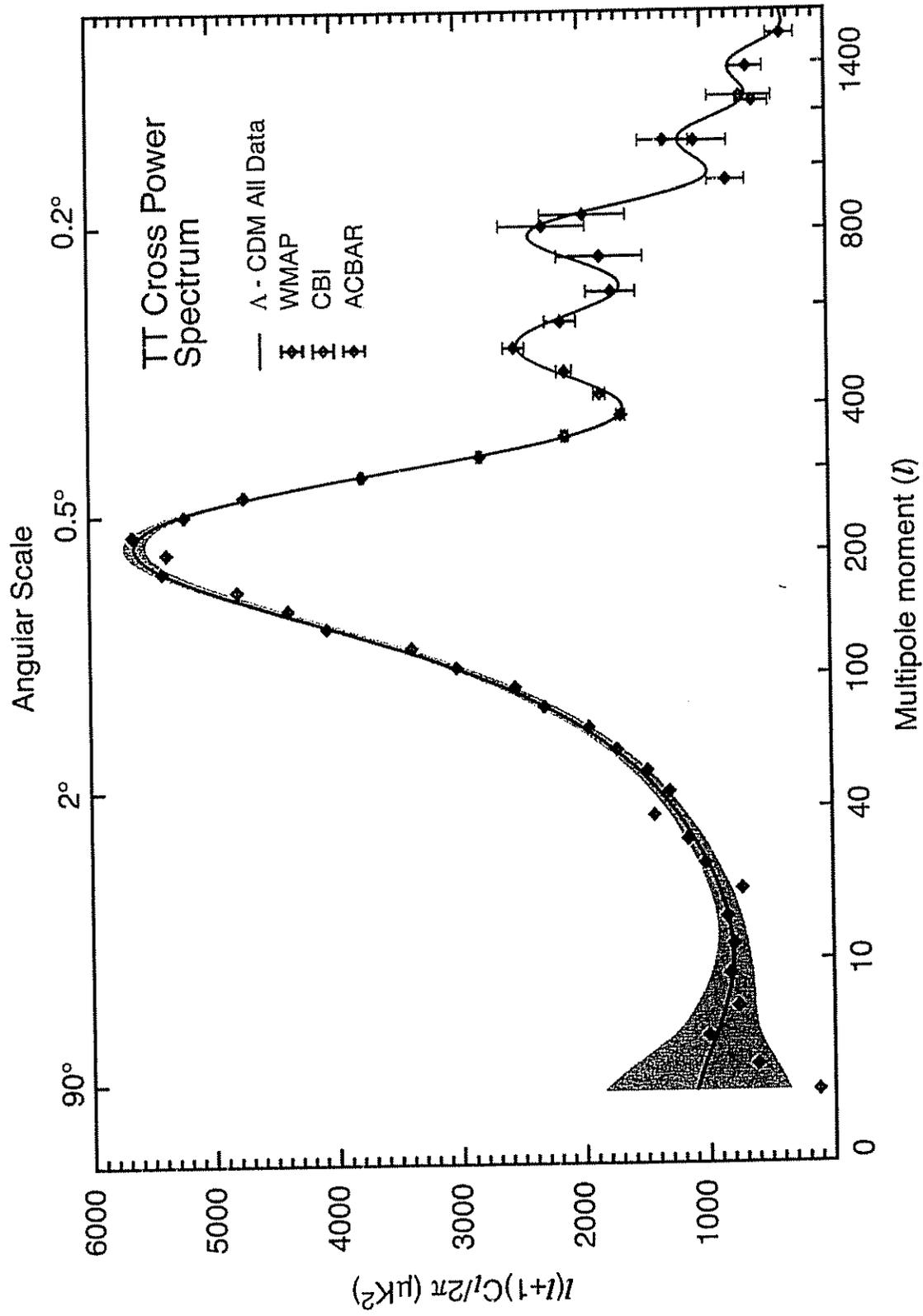
HVC - Complex G

Fig. from Wakker

Accreting Low-Metallicity Gas



CMB Data and Best Fit Power Law Λ CDM Model



DEUTERIUM

$$\Omega_b = 0.04 h_{70}^{-2}$$

$$\Omega_b h^2$$

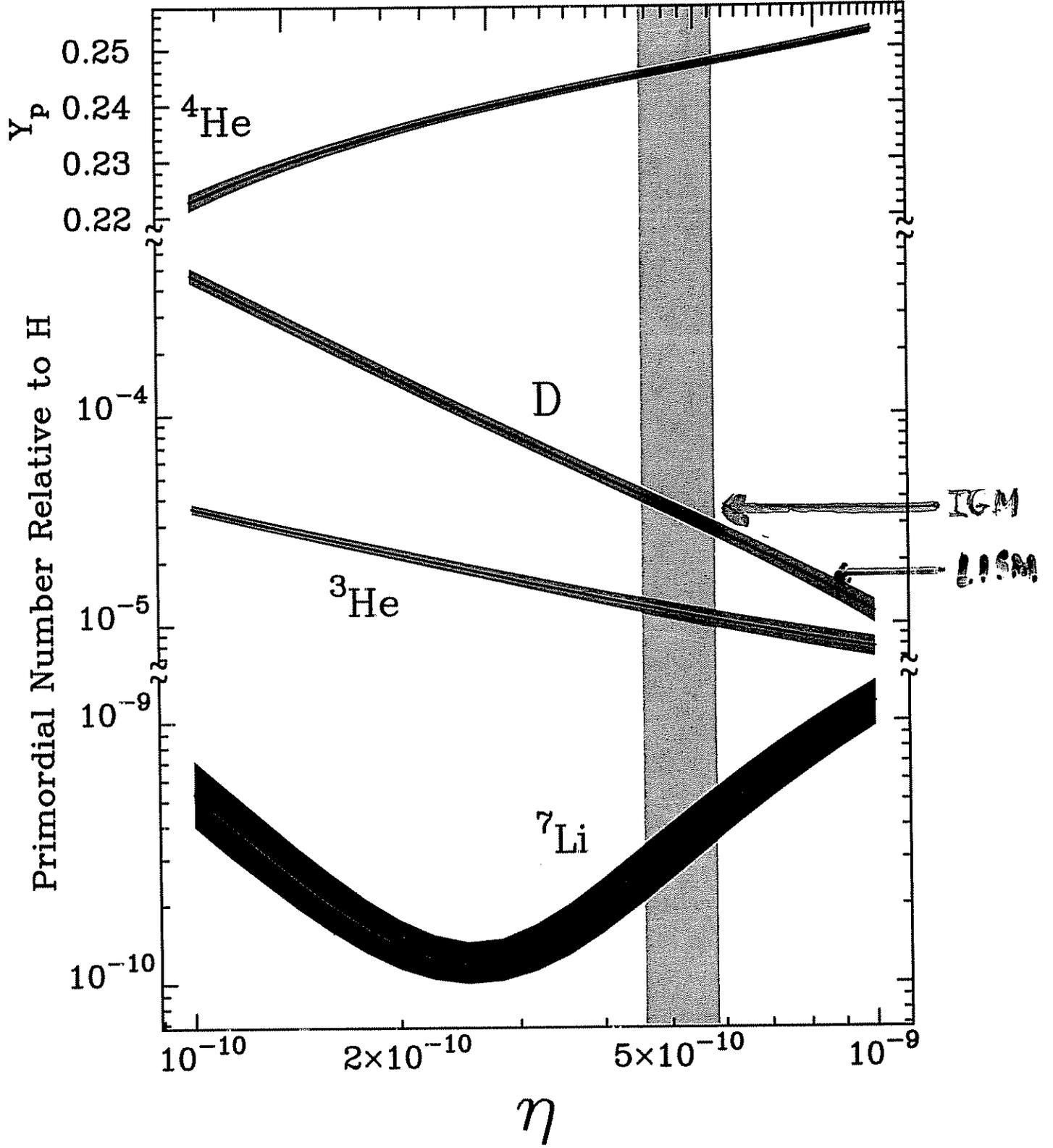


0.005

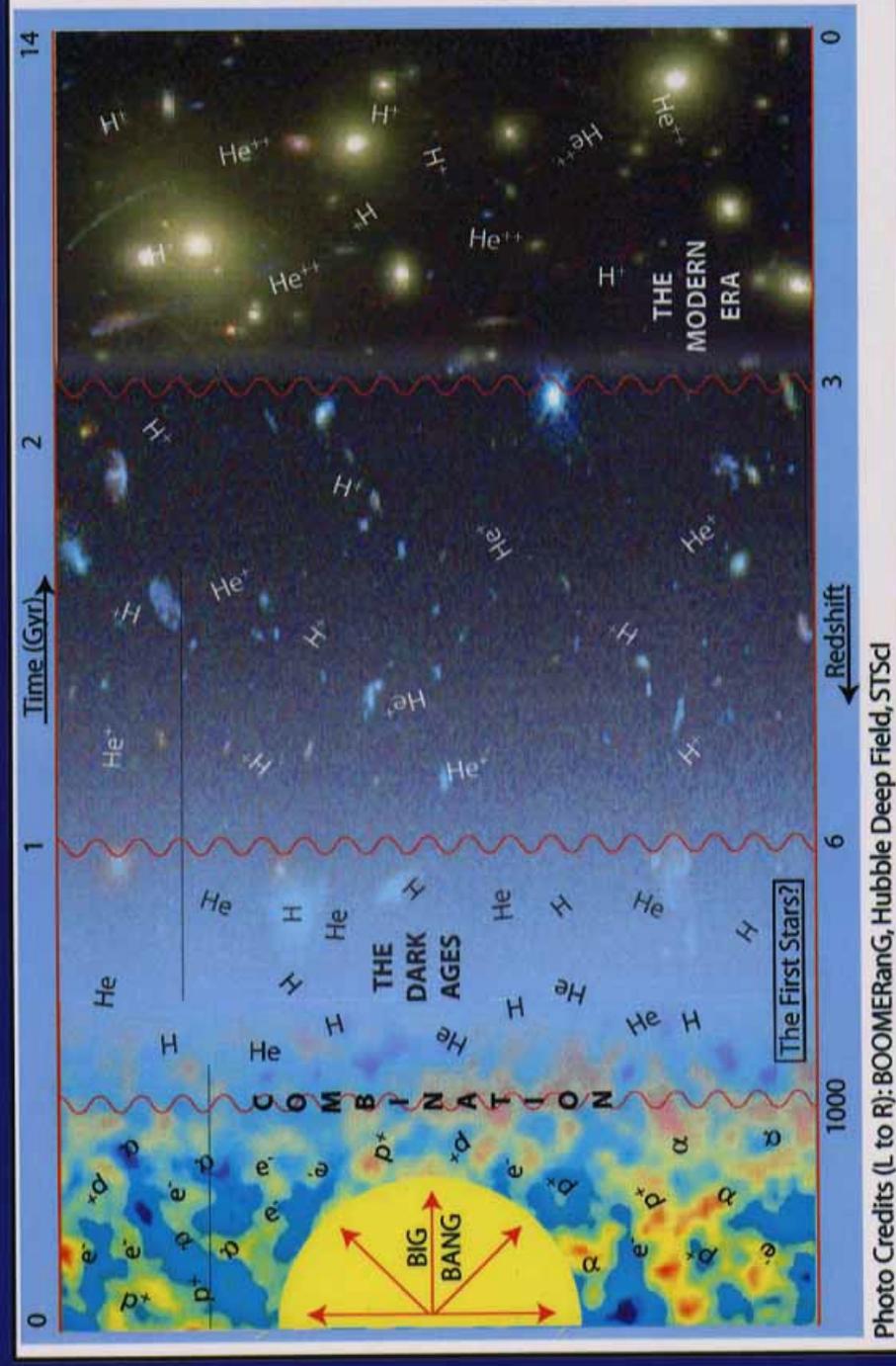
0.01

0.02

0.03

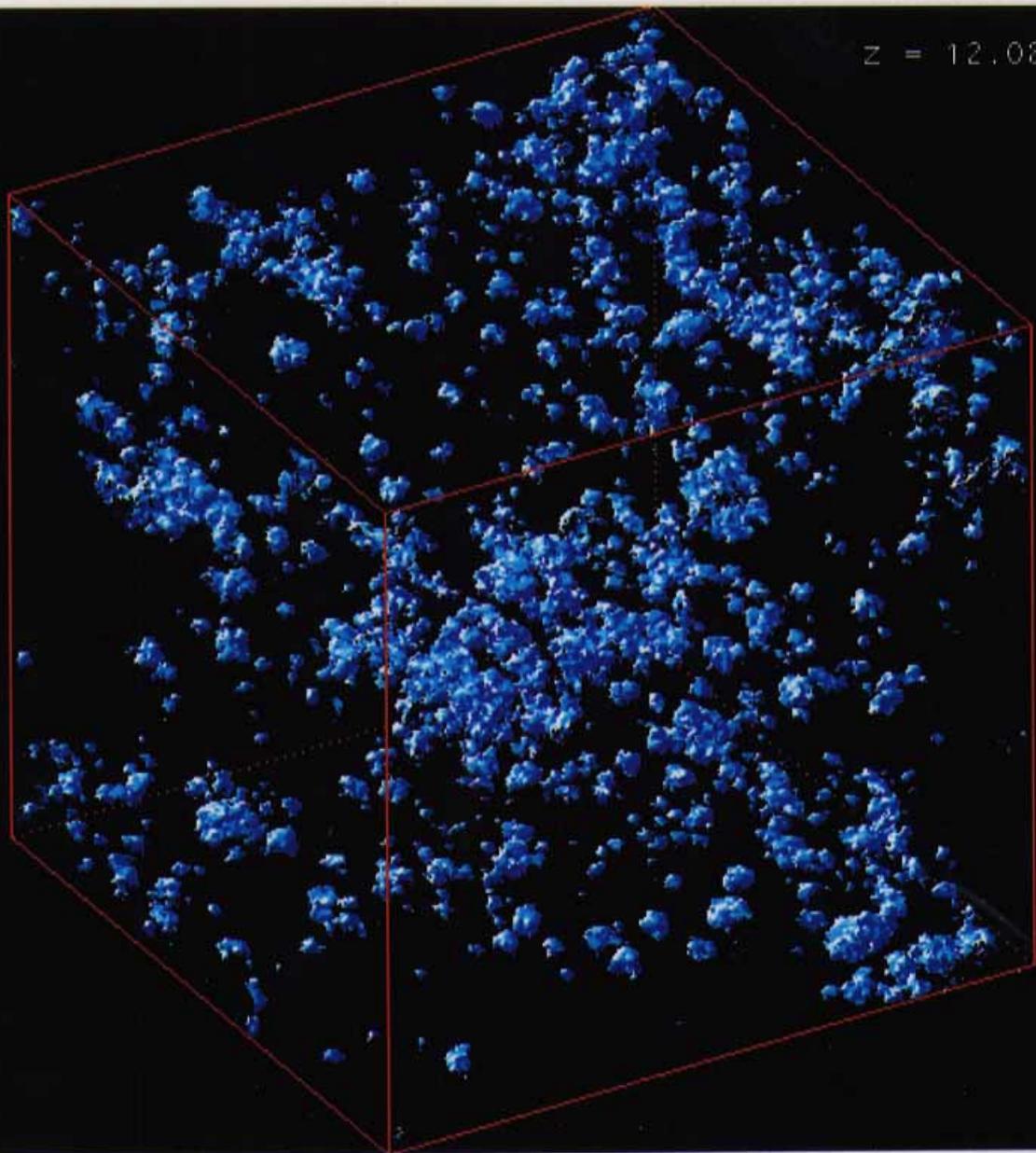


Reionization and the "Dark Ages"



The period between the "combination" and the H reionization at $z \sim 6$ is known as the "dark ages" - before the formation of galaxies and stars. In the common picture, H reionization is accomplished by stars at $z > 6$. The reionization of He is attributed to QSOs, which have harder ionizing spectra and reach a peak number density at $z = 3$.

$z = 12.08$

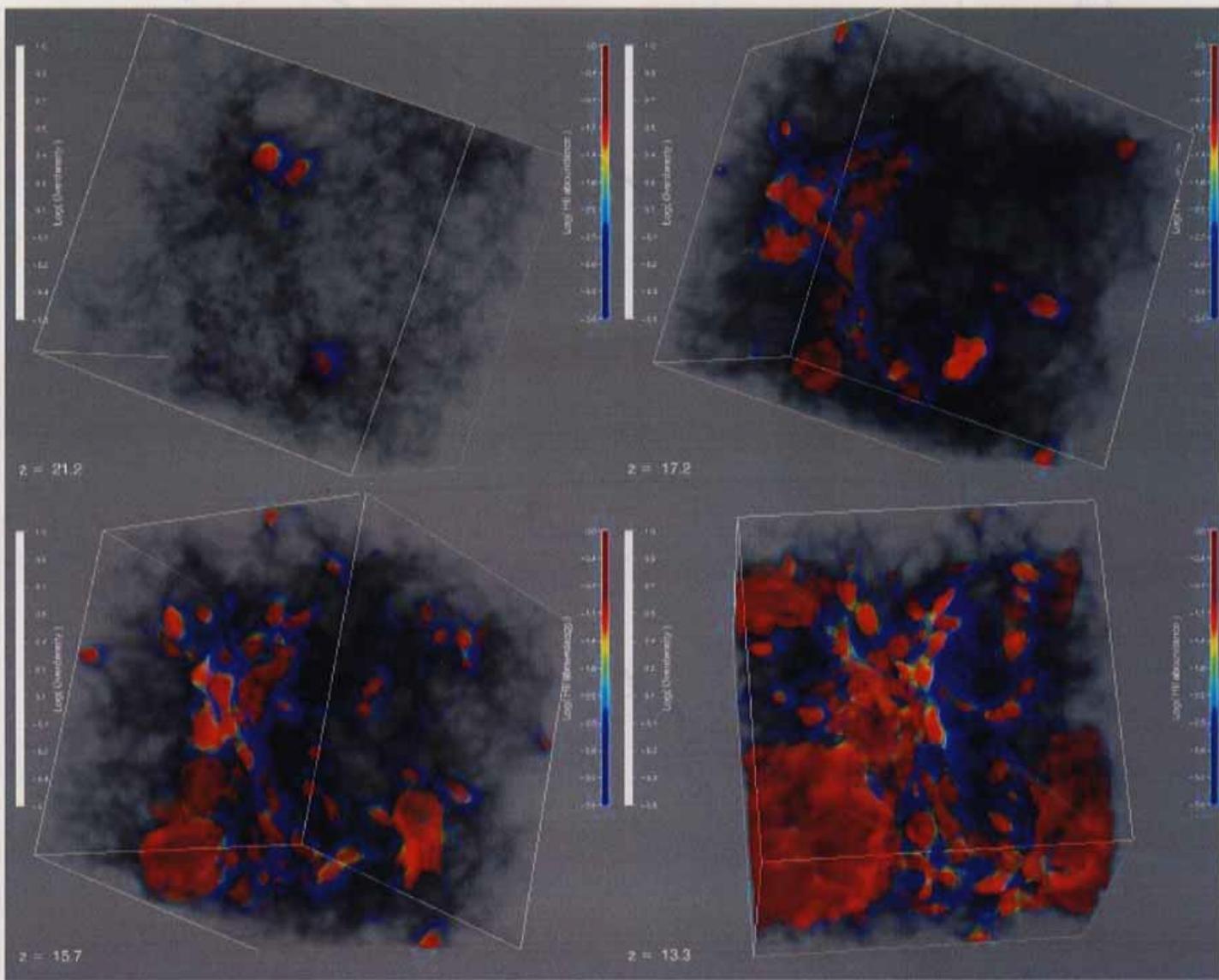


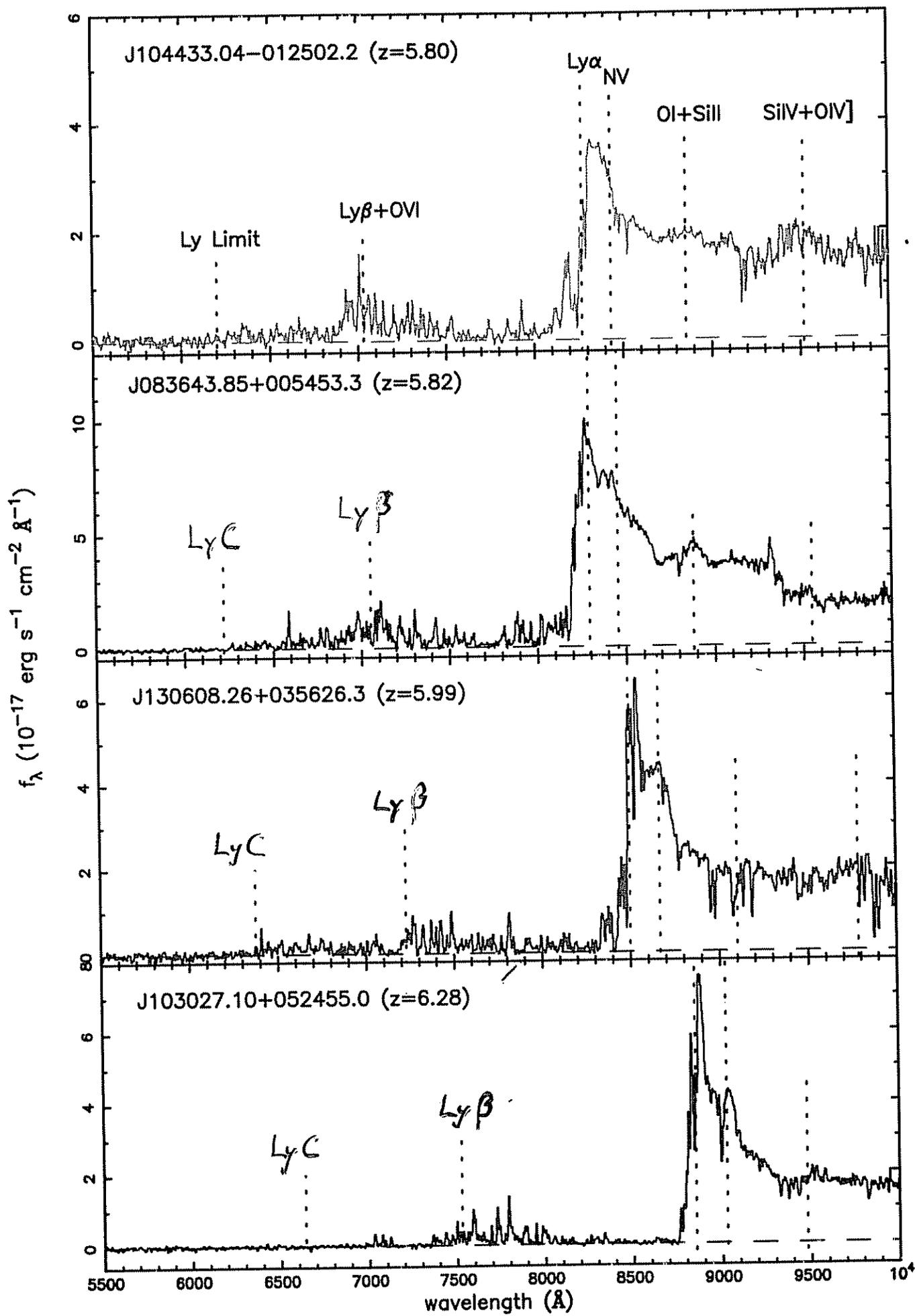
Ionization Fronts (First Starbursts)

($z \approx 10-15$)

Ricotti et al. (2002)

astro-ph/0106932



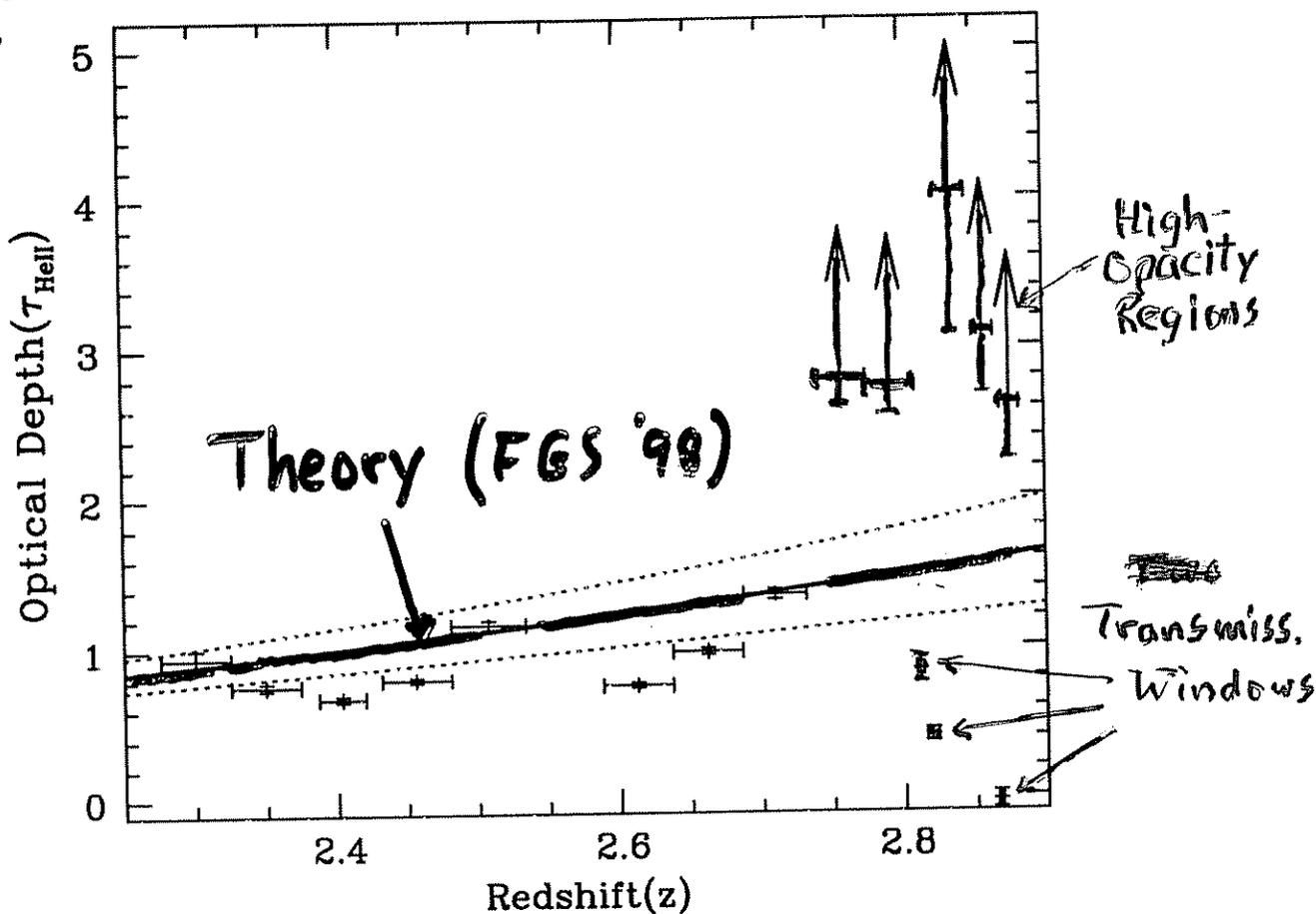


He⁺ Optical Depth [He II Ly α 304 Å]

(toward HE 2347-4342)

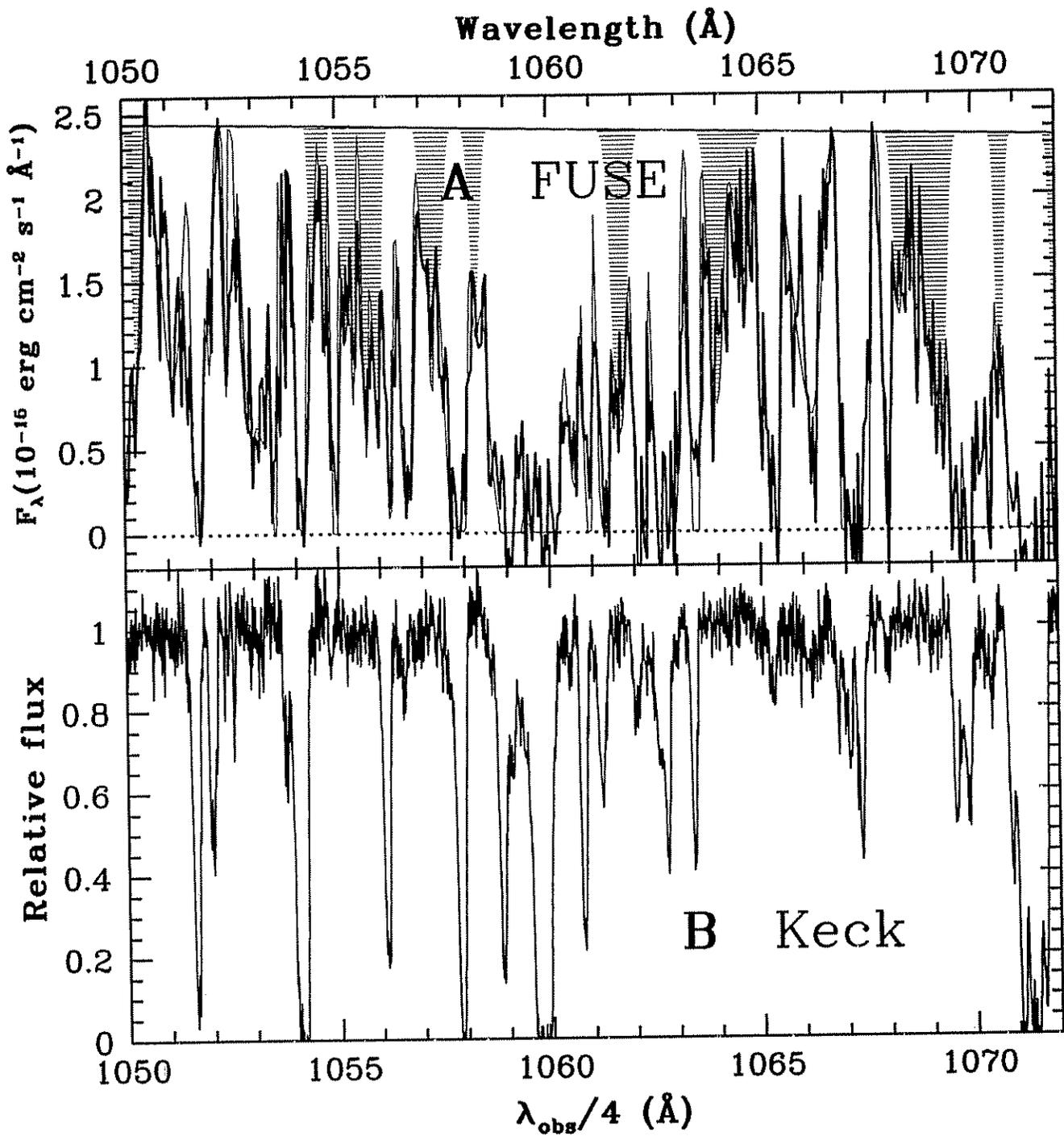
Kriss
et al. 2001

Science



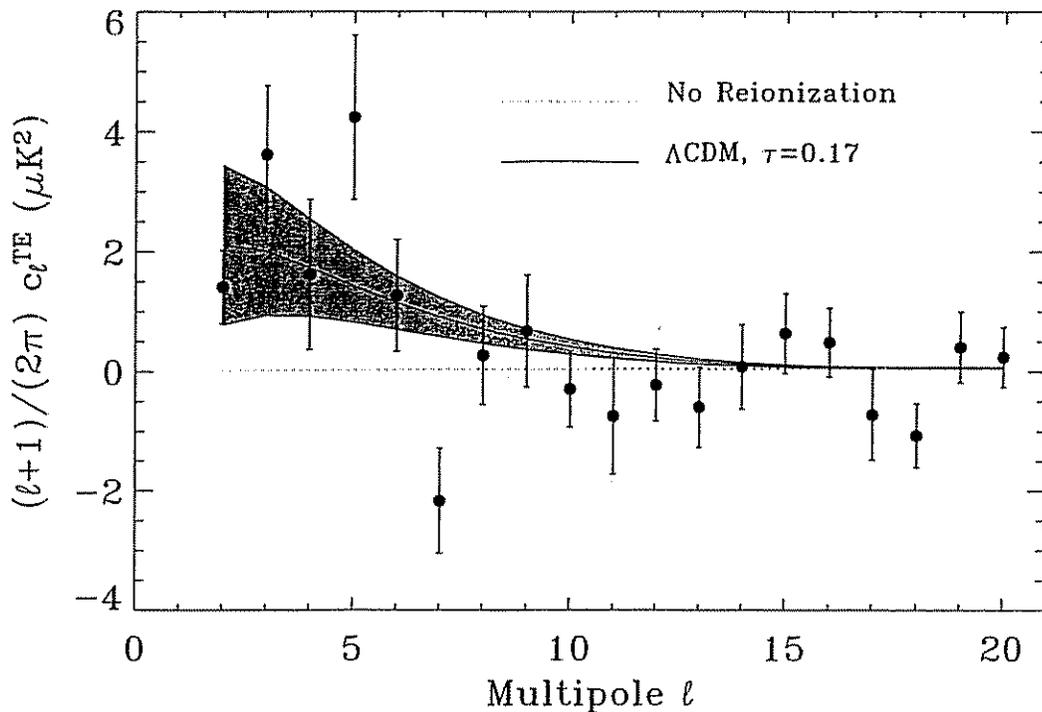
$$z_{\text{He}^+} \approx 2.8 \pm 0.2$$

He II Ly α ($z = 2.45 - 2.55$)



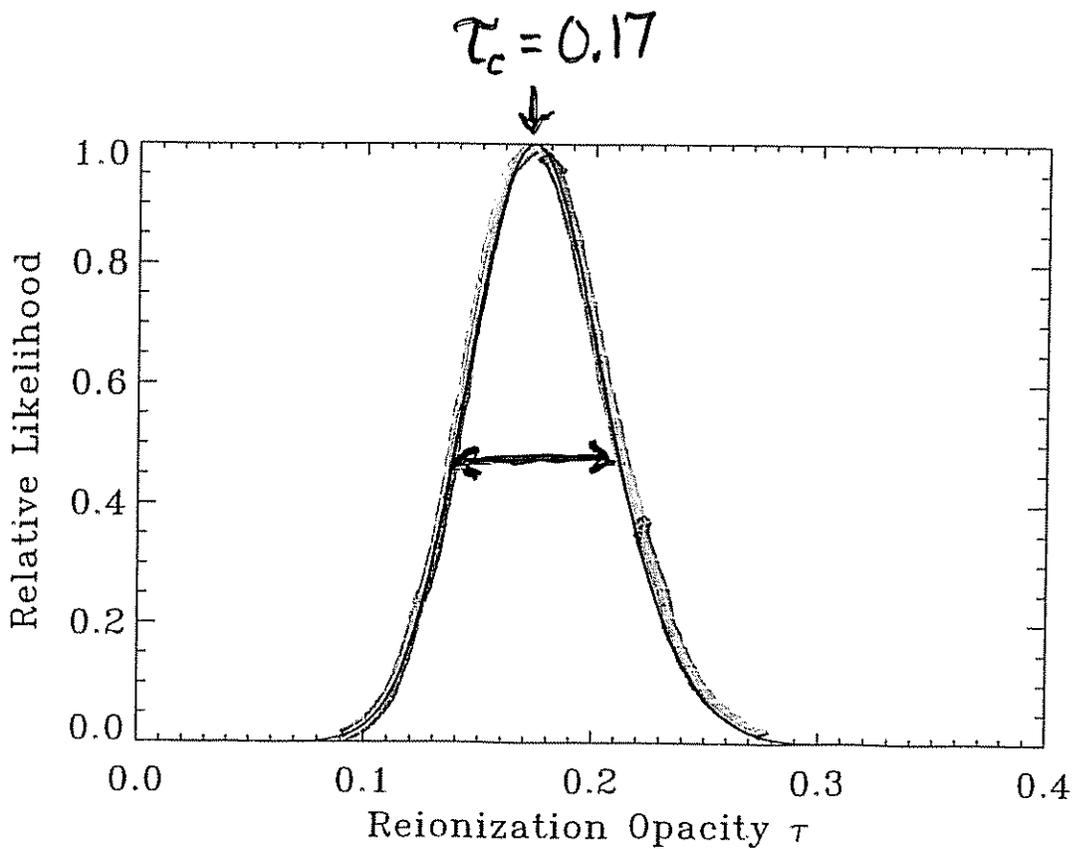
CMB opt. depth

Kogut et al.



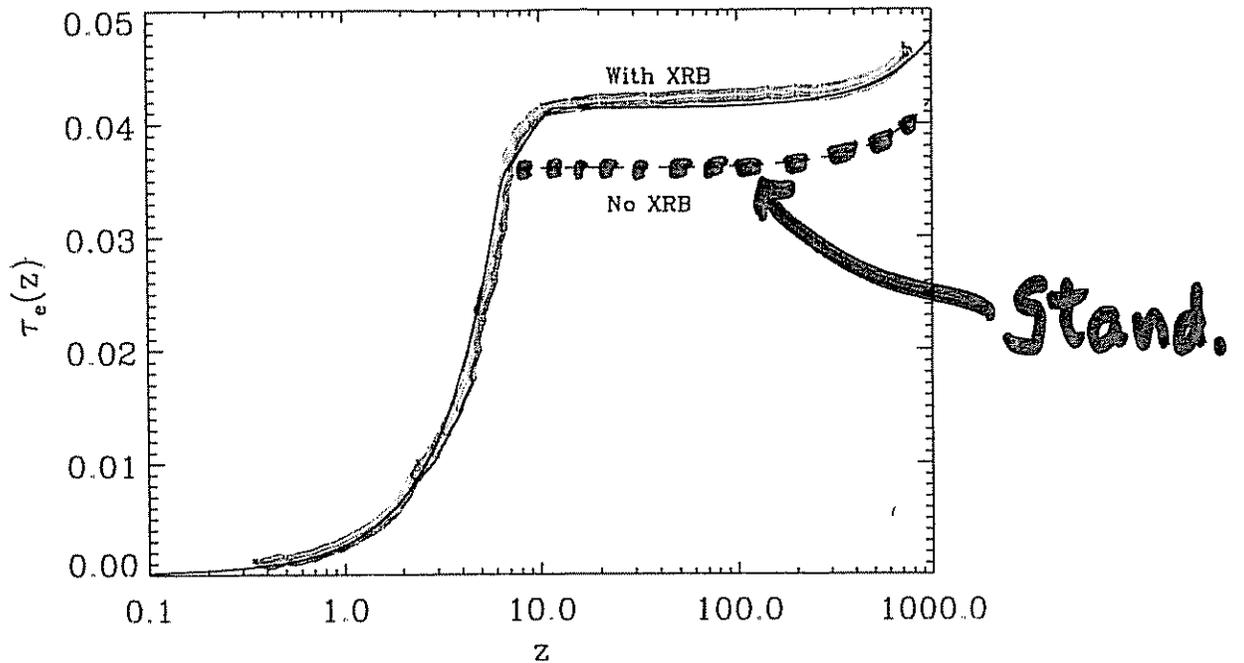
Bad χ^2

Hype!



HEATING AND IONIZATION OF THE INTERGALACTIC MEDIUM BY AN
EARLY X-RAY BACKGROUND

APARNA VENKATESAN, MARK L. GIROUX,¹ AND J. MICHAEL SHULL

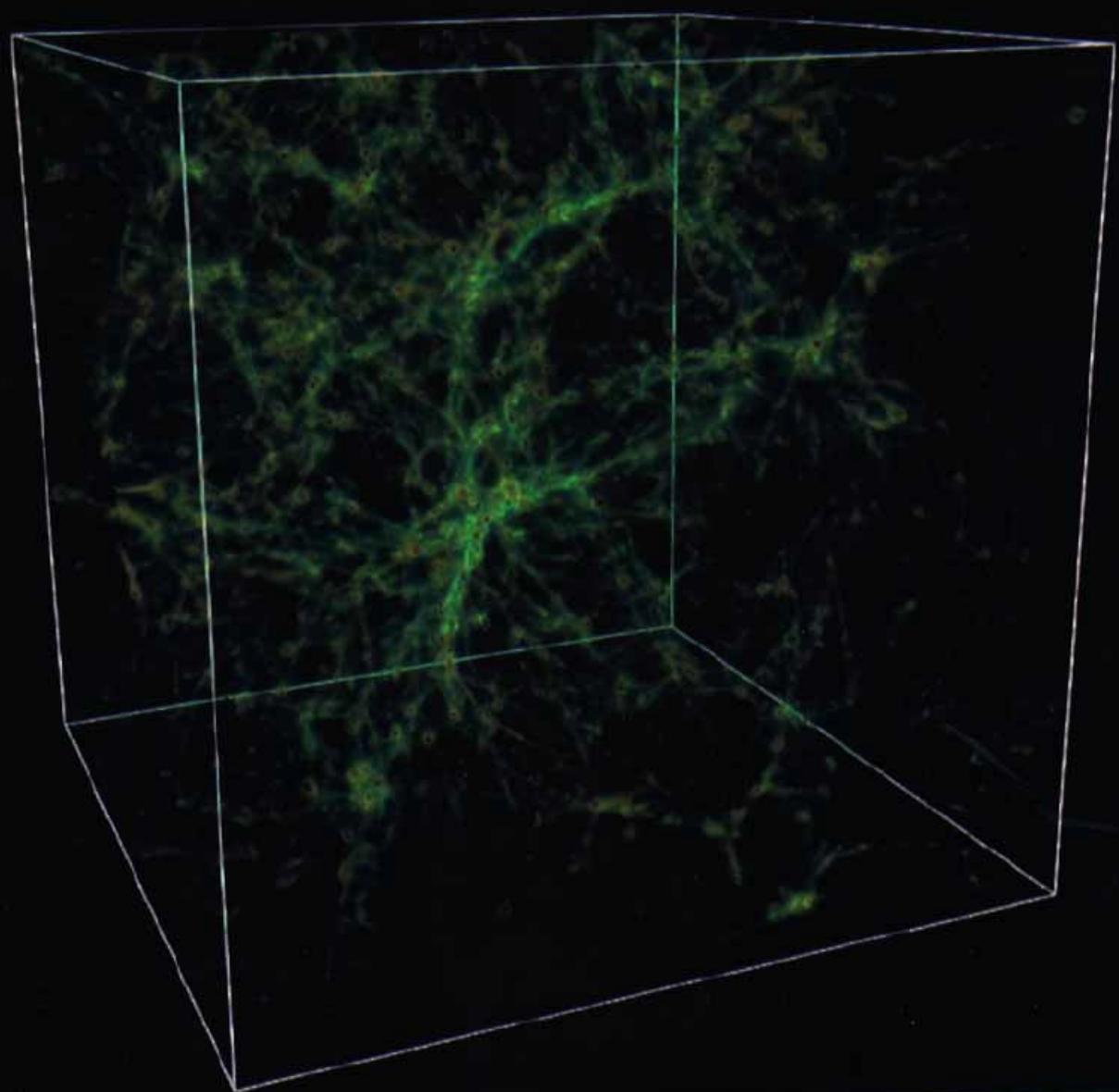


$$\tau_e \approx 0.04 - 0.05$$

[could be 0.09 with pop III
massive stars]

Cen 4 Astriker (1998)

"Hot IGM"
at $z \ll 1$



HST/STIS

(Penton, Stocke, Shell)

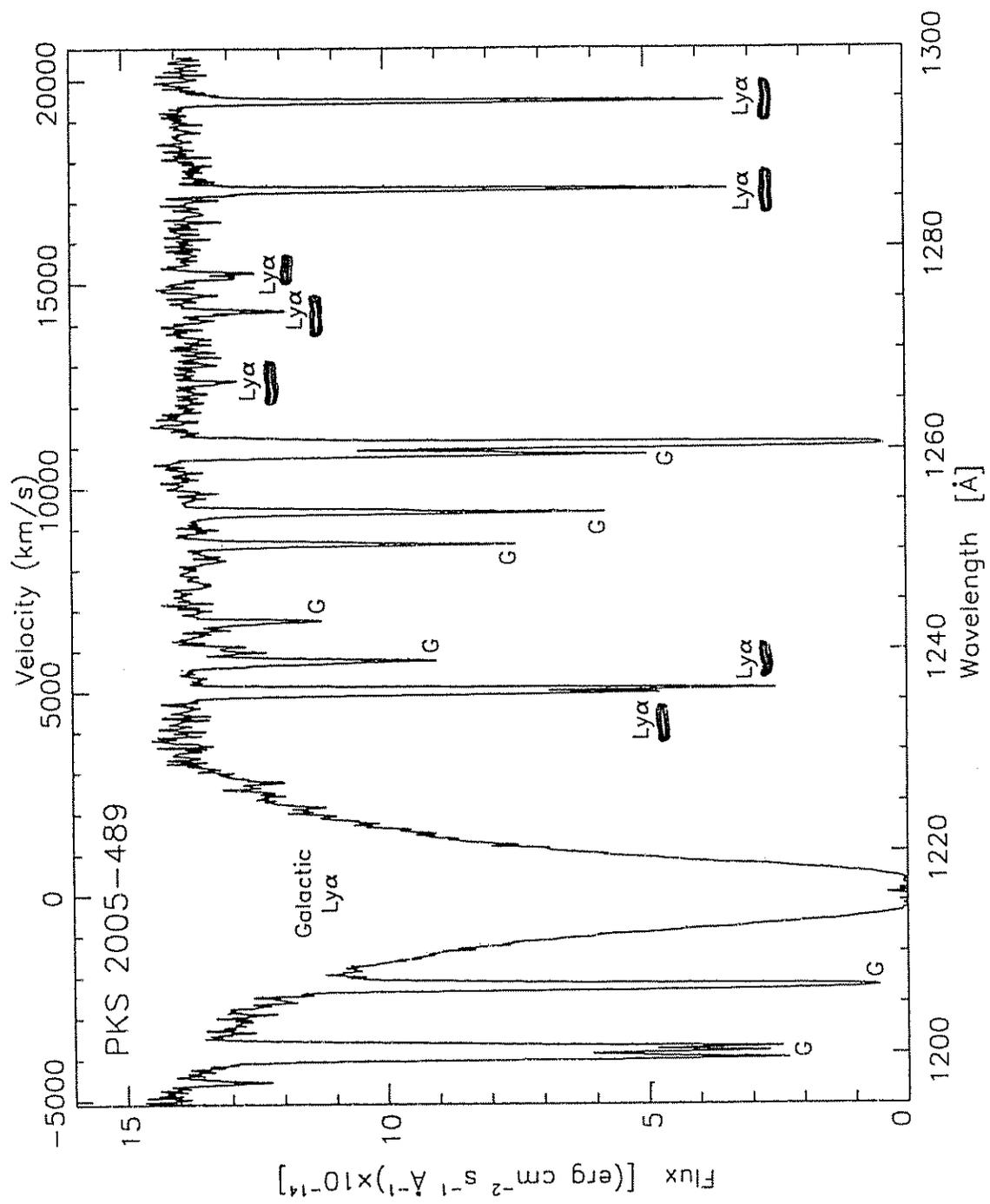
Still contains
20-30% of
baryons

$$\left(\frac{dN}{dz}\right) \sim 200$$



$$\text{to } N_{HI} = 10^{12.6} \text{ cm}^{-2}$$

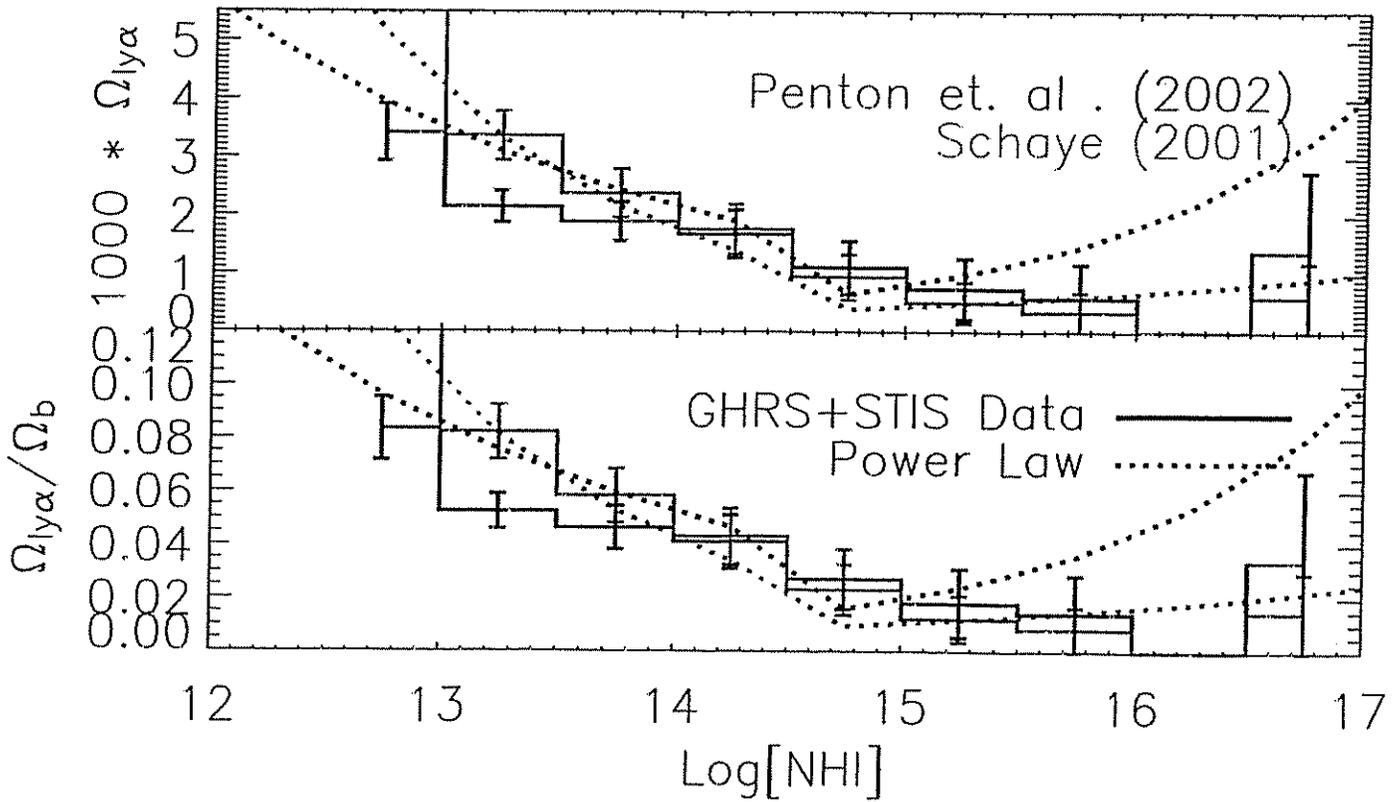
Low-Redshift IGM (Ly α)

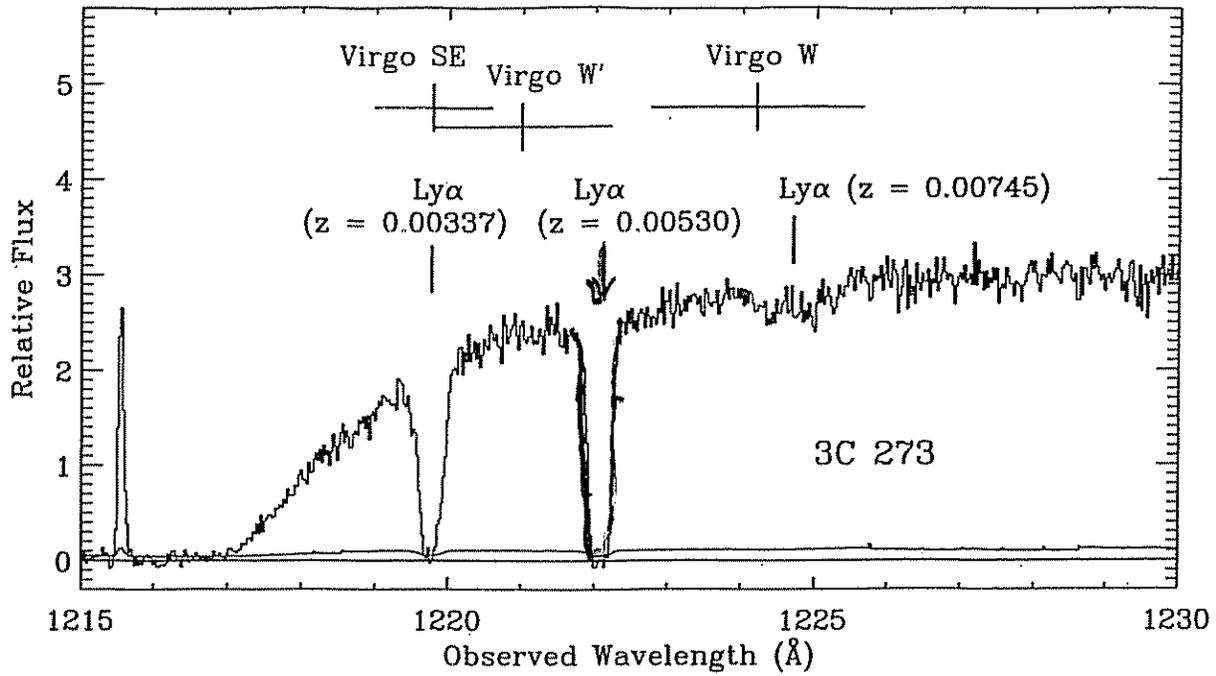


Ly α Forest ($z \leq 0.1$)

$$12.5 \leq \log N_{\text{HI}} \leq 17.0$$

$$\frac{\Omega_{\text{Ly}\alpha}}{\Omega_b} \approx 0.32 \pm 0.06$$



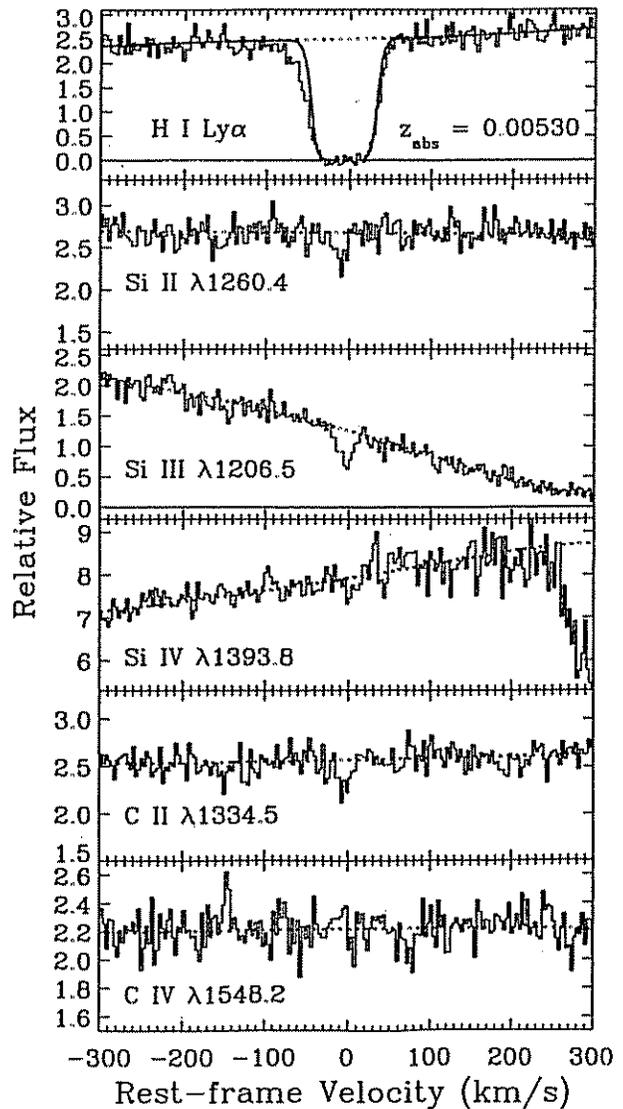


Tripp et al. (2002)
 [HST/STIS echelle]

abundances:

$$[C/H] = -1.2^{+0.3}_{-0.2}$$

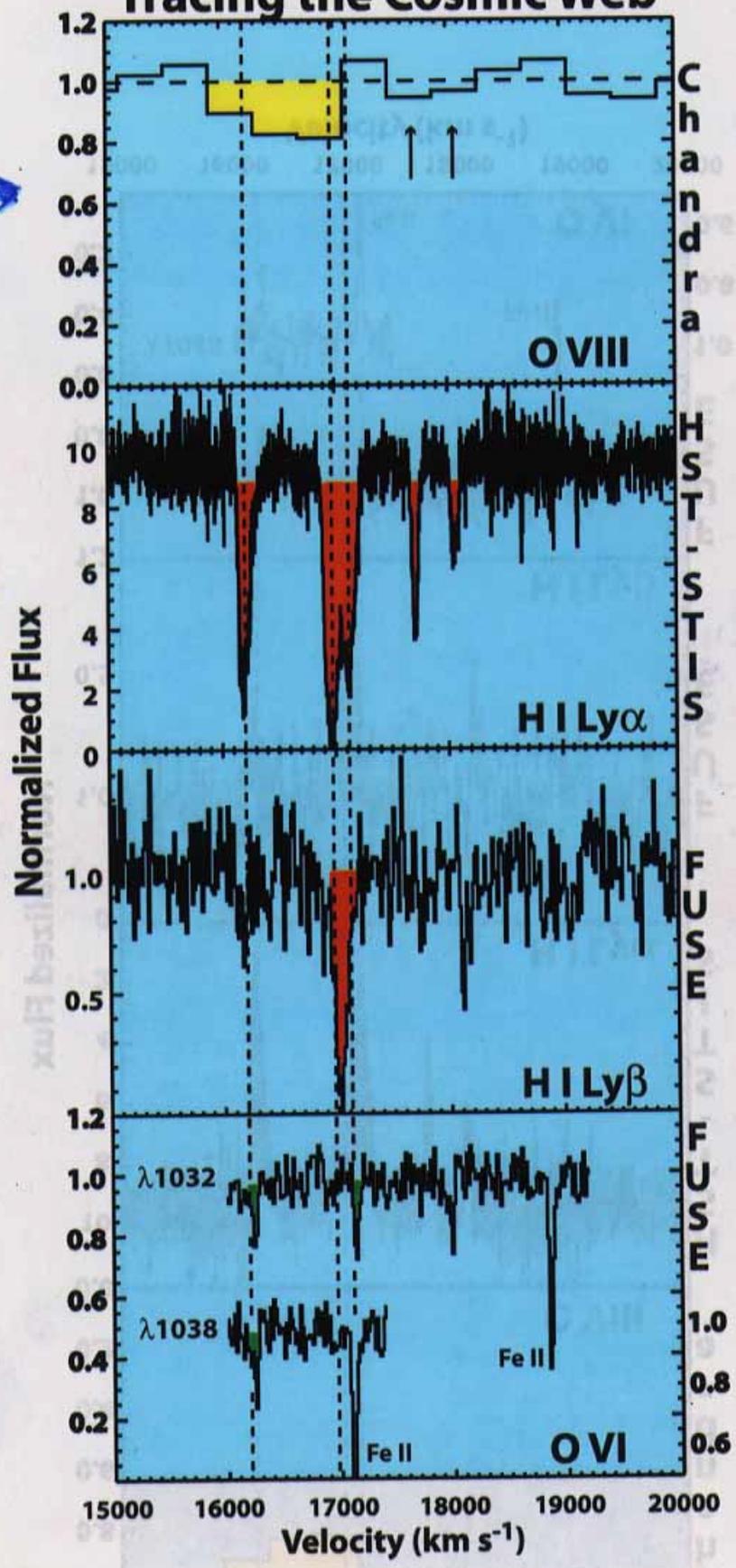
$$[Si/C] = +0.2 \pm 0.1$$



Tracing the Cosmic Web

Shull,
Tumlinson &
Giroux (2003)

Fang et al.
(2002) ApJL
↔



Chandra

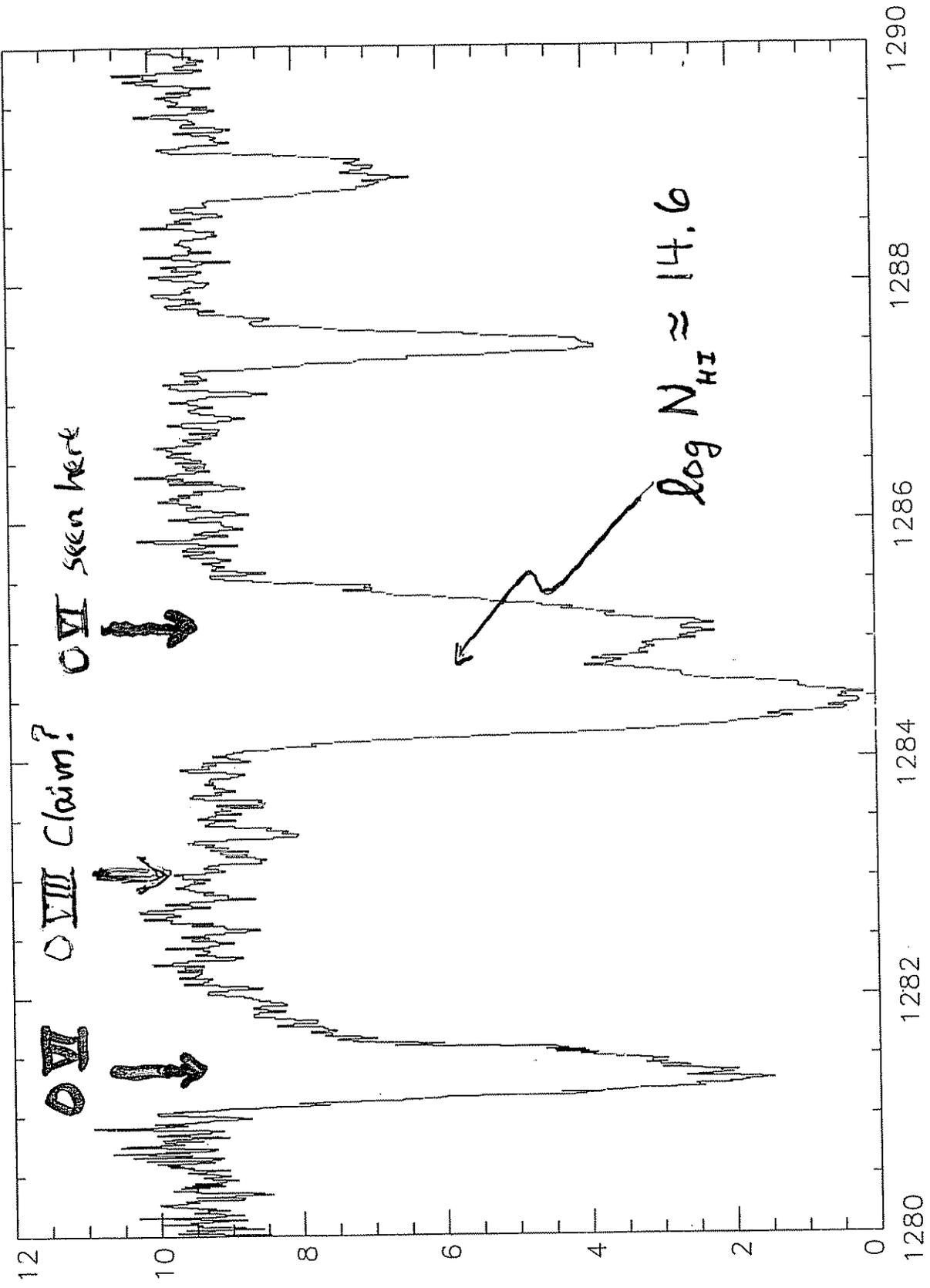
HST

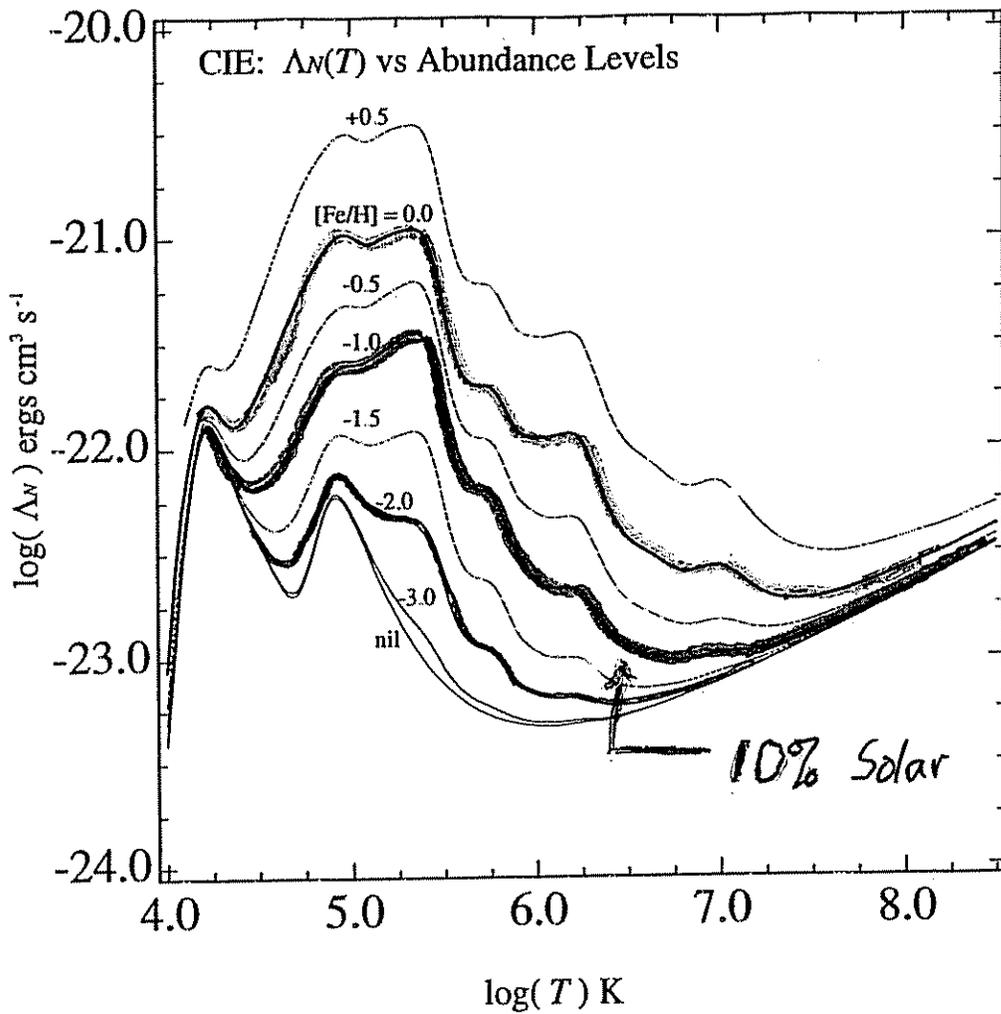
FUSE

FUSE

"Cluster" of Ly α Absorbers
(Shull et al. 1998)

PKS2155-304



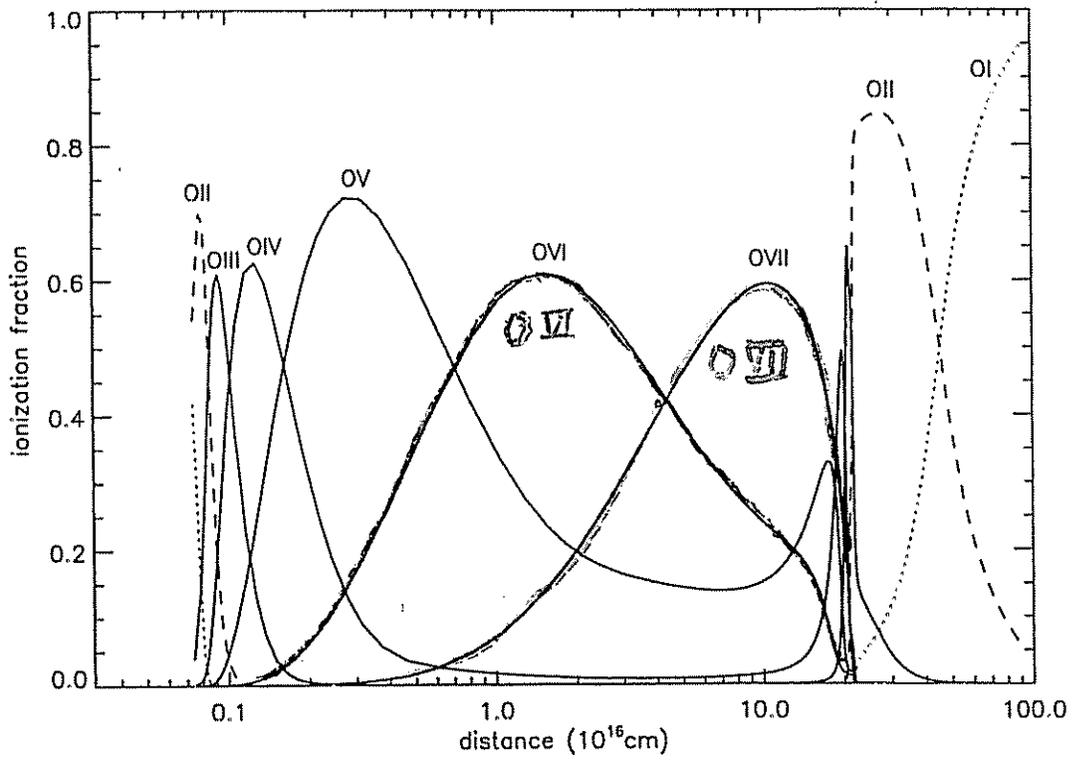
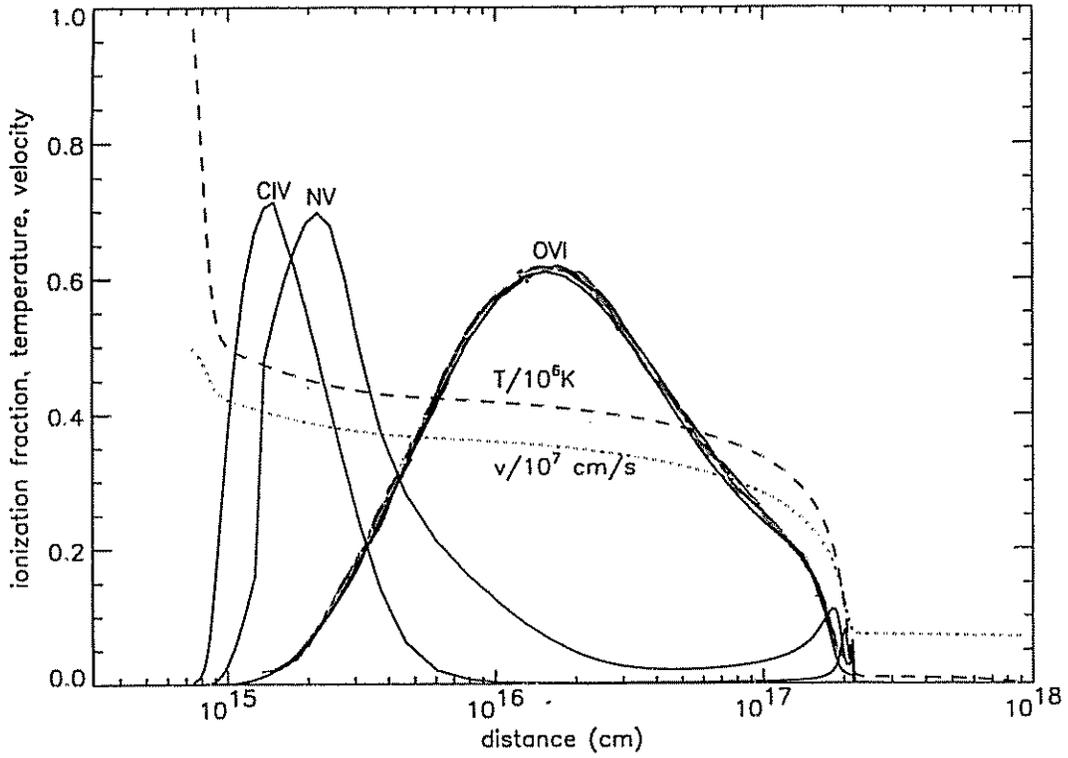


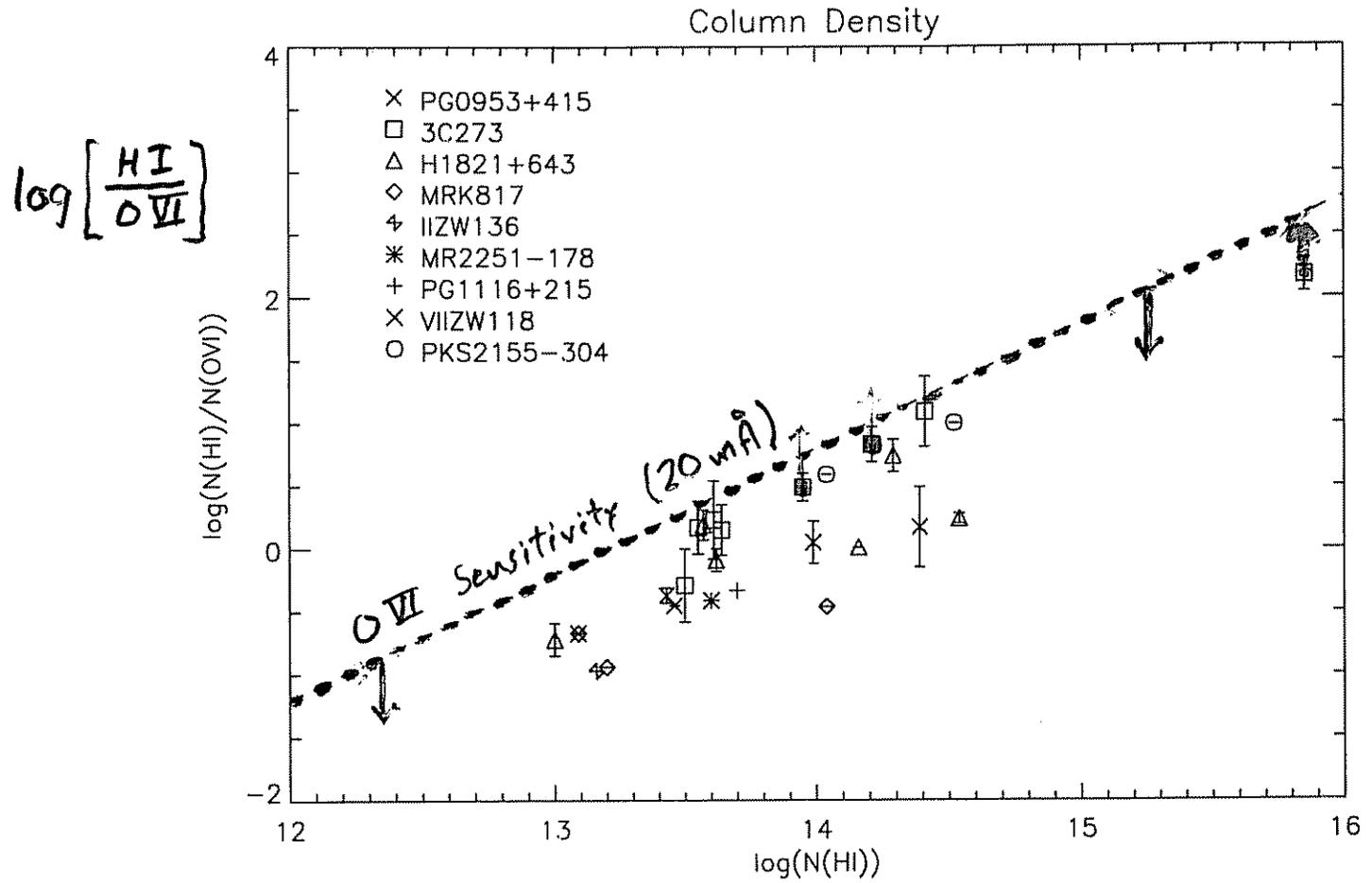
$$t_{\text{Cool}} = \frac{\frac{3}{2} k T}{n_e \Lambda} \approx \left(2 \times 10^{10} \text{ yrs} \right) \frac{T_{6.5}^2}{n_{-4} \Lambda_{-23}}$$

(δ ≈ 600)

Halo gas can't cool without a shock/compression trigger. [and radiative cooling]

200 km/s Shock





- OVI and HI Kinematic Assoc.
- Typical ratio $\left[\frac{HI}{OVI} \right] = 0.1-10$

BARYONS AT REDSHIFT $z = 0$

Baryon Content:

- $\Omega_b = 0.041 h_{70}^{-2}$ (D/H and CMB)
- $\langle \rho_{b,0} \rangle = (3.8 \pm 0.2) \times 10^{-31} \text{ g cm}^{-3}$
- $\langle n_{H,0} \rangle = 1.7 \times 10^{-7} \text{ cm}^{-3}$
- Baryon $f_b = \Omega_b / \Omega_m = 0.14 \pm 0.01$

Major Baryon Repositories:

- $\Omega_{\text{Gal}} = [0.003 \pm 0.001] h_{70}^2$ ← $7 \pm 3\%$
- $\Omega_{21\text{cm}} = [0.00039 - 0.00063] h_{70}^{-1}$ ← 1%
- $\Omega_{\text{Ly}\alpha} = [0.008 - 0.012] h_{70}^{-1}$ ← 30% ?
- $\Omega_{\text{OVI}} = [0.003 - 0.008] h_{70}^{-1}$ ← $5-10\%$?
- $\Omega_{\text{OVIII}} = [???] h_{70}^{-1}$ ← TBD
(X-ray spectra)

O VII and O VIII